

# **Deterministic Modeling of Water Entry and Drop of An Arbitrary Three-Dimensional Body — A Building Block for Stochastic Model Development**

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## **LONG-TERM GOAL**

The ultimate goal is to develop a robust and accurate physics-based hydrodynamics model, which is capable of reliably predicting the motion of a mine-shaped three-dimensional object impacting water surface from air and subsequently dropping through water toward the sea bottom. This deterministic model provides the velocity and orientation of mines as the key input for bottom impact/burial prediction and is an essential building block in stochastic model development for mine burial predictions.

## **OBJECTIVES**

The specific objectives of the effort include:

- To develop theoretical and computational predictions of the motion of a three-dimensional body impacting the water surface at arbitrary entry velocity and angle
- To develop an effective dynamical model for the simulation of the six degree-of-freedom motions of a three-dimensional body dropping in the water including viscous effects
- To conduct scaled laboratory tests at the water tunnel of MIT to establish a data base of the drag coefficients of cylindrical-shaped mines at various velocities and orientations
- To provide deterministic data sets of the transfer functions of the velocity and motion of mine-shaped bodies during their entry into water and dropping toward the bottom for probabilistic mine burial prediction

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## **APPROACH**

For water impact, to account for the large range of physical/geometrical parameters, we develop and apply a multi-level approach utilizing theoretical, semi-analytic, and direct computational tools in the respective regimes in which they are valid and most efficient. Specifically, we develop: (i) an analytic model based on the theory of von Karman for water impact of arbitrary three-dimensional bodies; (ii) an effective semi-analytic model using the generalized Wagner's approach (Mei, Liu & Yue 1999) for water entry of mine-shaped bodies at arbitrary entry velocity and angle; and (iii) a fully-nonlinear numerical simulation model based on the Mixed-Euler-Lagrangian approach (Liu, Xue & Yue 2001) for general water impact of three-dimensional bodies including the effects of free-surface jet and cavity. For the drop of a three-dimensional bluff body in the water, we develop a dynamical model for the prediction of six degree-of-freedom motions of the body. The effect of vortex shedding, flow separation and cavitation is accounted for based on the use of empirical quasi-static drag coefficient. To determine the drag coefficients associated with vortex shedding and flow separation, we conduct scaled laboratory tests in the water tunnel of MIT.

For calibration and validation of the water entry and drop models, the model predictions are compared with the tank and field drop tests conducted by the other research team also funded by the ONR mine burial research program.

## **WORK COMPLETED**

The major work completed includes:

- Development of a simple analytic model for the prediction of the horizontal and vertical motions of cylindrical mines released inside water, and calibration and validation of the model against available field-test data.
- Development of water entry models for three-dimensional mine-shaped bodies impacting water surface at arbitrary velocity and entry angle using both the von Karman method and the generalized Wagner's approach. The models are validated by comparisons to available existing theoretical solutions and tank/field test data.
- Development and validation of an effective dynamical model for the prediction of the six degree-of-freedom motions of a three-dimensional body dropping through water; and development of an effective algorithm to account for viscous effects on the motions of mine-shaped bodies.
- Providing assistance and guidance to the mine drop test group, led by Dr. Philip Valent of Naval Research Laboratory, Stennis Space Center, for the design and conduction of tank and field drop tests.
- Conduction of scaled laboratory tests of the drag coefficients of mines in the water tunnel of MIT and establishment of database of drag coefficients for cylindrical-shaped mines.
- Investigation of motion features of mines dropping in the water, identification of key characteristic patterns of the mine motions, and comparisons of the model predictions to tank and field tests.

## RESULTS

The present model predicts many of the salient motion features of mines observed in tank and field drop tests, and substantially improves the accuracy and reliability over existing models now in use (Kim, Liu & Yue 2002). While the success so far is substantial, the present prediction model still needs to be improved and further developed for reliable mine burial prediction when physics such as air-trapping, off-plane excitation, and complex environments come into play. These are found to be not uncommon in field and tank observations but are as yet not properly considered in the present model.

Figures 1 and 2 show two sample qualitative comparisons between the experimental observations and the numerical model predictions. The experimental data are from the tank drop tests conducted at NSWCCD (Valent & Holland 2001). The numerical results shown are obtained with two different approaches: the method applied in the existing model (IMPACT 25/28) and the new model developed in this effort. When the mass center of a mine deviates slightly from the buoyancy center, as shown in figure 1a, the mine is observed in the experiments to undergo an oscillatory pitch motion (which is often coined as “see-saw”) during its fall toward tank bottom. IMPACT 25/28 does not predict such a sea-saw motion pattern (see figure 1b), while our new model predicts a similar sea-saw motion (see figure 1c) as observed in the experiments. In the experiments, it is often observed that (initially) vertical mines change the orientation to horizontal during the dropping, as shown in figure 2a. Through theoretical analyses, we find that this is due to the effect of the instability of slender mine motion to transverse perturbations. With the inclusion of this effect, the new model is capable of predicting such changes in mine orientation (see figure 2c), while IMPACT 25/28 gives a completely incorrect prediction (see figure 2b). In the viewpoint of providing the input for mine burial prediction, the difference between figure 2b and 2c is dramatic, which may lead to completely different predictions of mine penetration into soil.

During the past year, we have also conducted quantitative validation of the model. We have compared the motion acceleration measured in the field tests with the results of our new model, and a fair agreement could be observed in some simple cases where the experimental data is available. In particular, the agreement was excellent when the body attitude is purely horizontal or vertical during its falling. However, we also found that the new model needs more improvement and development, especially in accounting for the air-trapping effect and off-plane excitations.

## IMPACT/APPLICATION

Proper modeling of the hydrodynamics of mines impacting the water surface and dropping through the water to the bottom is essential for reliable mine burial predictions. Our work provides the necessary deterministic transfer functions of the velocity and orientation of mines in water entry and drop. These are essential input to the stochastic mine burial prediction model. Such accurate predictions of the mine motion in water cannot be achieved using the existing tools such as IMPACT 25/28.

## TRANSITIONS

The present hydrodynamic model developed in this study will be incorporated into a stochastic model for the prediction of mine burial. Such a stochastic model can provide useful information on mine burial for mine deployment or sweeping.

## PUBLICATIONS

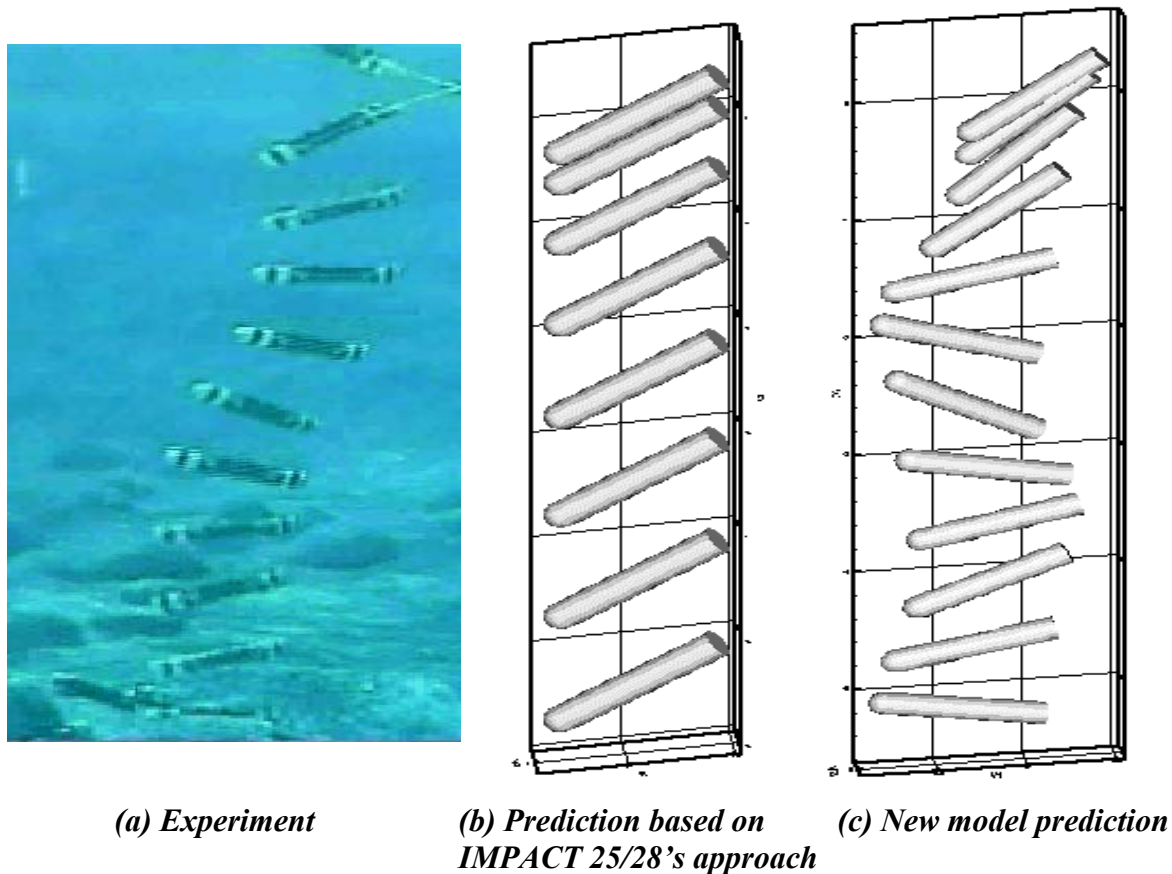
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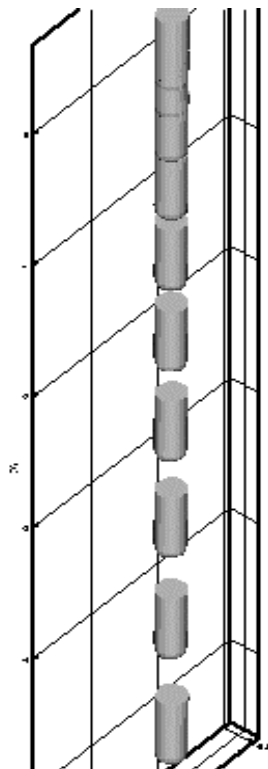
Valent, P. & Holland, T. 2001 Quick look report, model mine hydrodynamics tests, NSW-Cardrock, 10-14 September 2001, NRL Internal Memorandum.



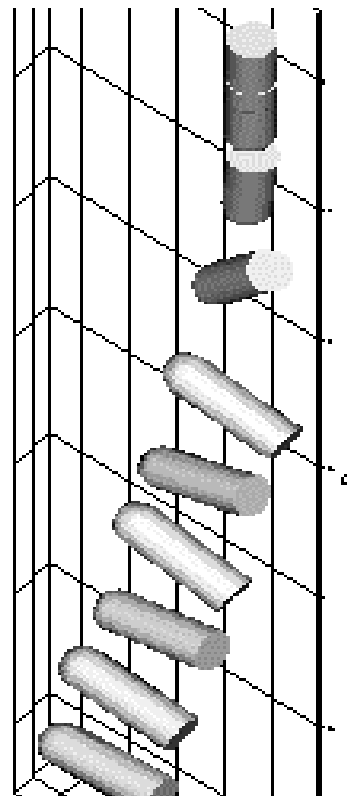
**Figure 1. Comparison of the mine motion pattern between numerical model prediction and experimental observation. The new model prediction agrees well with the observation while the existing model IMPACT 25/28 does not predict the observed sea-saw motion pattern.**



*(a) Experiment*



*(b) Prediction based on  
IMPACT 25/28's approach*



*(c) New model prediction*

***Figure 2. Comparison of the mine motion pattern between numerical model prediction and experimental observation. IMPACT 25/28 does not predict the change of mine orientation from vertical to horizontal while the new model prediction agrees well with the observation.***